

THE ORIGIN OF THE KNEE IN THE COSMIC-RAY ENERGY SPECTRUM

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A sudden steepening of the cosmic-ray energy spectrum (the knee) is observed at an energy of about 3 PeV (1 PeV = 10^{15} eV). The recent results on extensive air showers allow us to conclude that: a) the knee has an astrophysical origin; b) the 'sharpness' and the fine structure of the knee rule out 'Galactic Modulation' as the origin of the knee; c) most likely the knee is the result of the explosion of a single, recent, nearby supernova.

1 Introduction

Cosmic rays spread over 11 decades of energy with an almost featureless power law spectrum. There are just two structures which are well established: the steepening at an energy of about $3 \cdot 10^6$ GeV and the flattening near 10^{10} GeV. The first is called *the knee*, the second is *the ankle*. Both features are crucial for understanding cosmic-ray origin and propagation. We concentrate on the knee origin, because there has been progress in its study during the last few years.

2 Models for the Origin of the Knee

Models of the knee proposed to date can be divided into two distinct classes: *astrophysical* and *interaction* models. The *astrophysical* models attribute the change in the spectra of the observed extensive air showers (EAS) to the change in the energy spectra of the primary cosmic rays. The *interaction* models imply that the primary energy spectrum has no such sharp change and the observed steepening of EAS size spectra is due to the sudden change of the nature of the interactions between the high energy particles of primary cosmic rays and the atmosphere. The astrophysical models are more numerous and developed. They might be also subdivided into two classes: the *source* models, with a change of sources or their acceleration mechanisms, and the *propagation* models, with a change of the cosmic-ray propagation between the source and the observer.

3 EAS Characteristics in the Knee Region

The basic characteristics which are important for the analysis of the knee origin are the energy spectrum, the mass composition of the primary particles and the anisotropy of their arrival directions. The first two determine the spectral shape and ratios of different EAS components.

3.1 Shape of the EAS size spectra

The measurements of EAS clearly show¹ that:

- * the size spectra of *all* components have a sharp knee at the values corresponding to a primary energy of about 3 PeV.

This is an important result because *it does not leave room for the interaction models*.

- * the EAS electron size corresponding to the knee position decreases with the atmospheric depth in accordance with expectation, if the knee occurs at a fixed primary energy.

* the sharpness of the knee (1.3 ± 0.1) exceeds that expected in the Galactic Modulation model (~ 0.3).

* the knee has the fine structure. If all the electron size spectra are normalized at their knee position, then, at the size which is by the factor of 4 higher, there is another intensity peak. The second peak is found also in Cherenkov light spectra, which proves its astrophysical origin. These results are shown in Figure 1. Here, the fine structure of the 40 EAS size and 5 Cherenkov light spectra are shown for the excess of the intensity over the running mean¹. The presence of the second peak is seen beyond the error bars both in EAS size and in Cherenkov light spectra. The magnitude of sharpness and the existence of the second intensity peak are important for

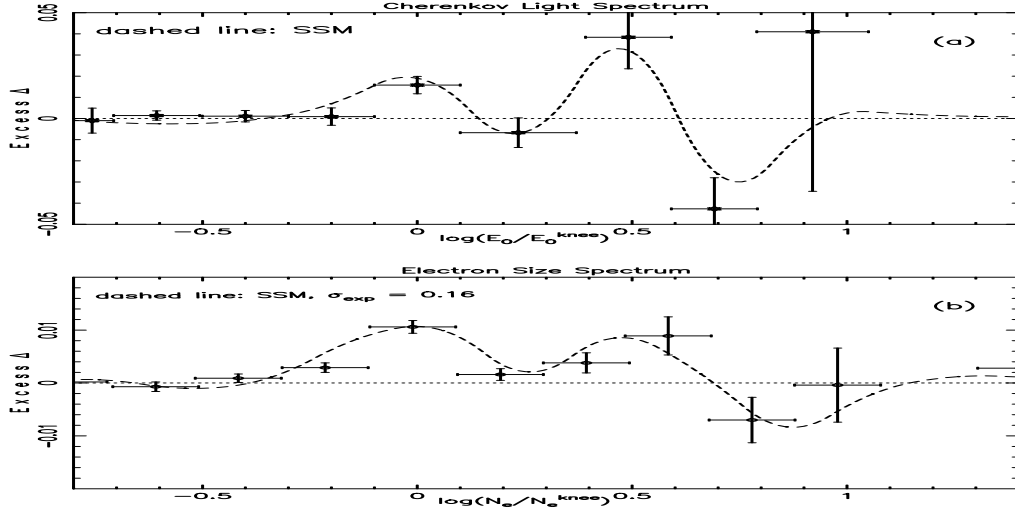


Figure 1: Excess over the running mean. The results relate to the average excess, in $\Delta \log(E_0/E_0^{knee})$ and $\Delta \log(N_e/N_e^{knee})$ bins equal to 0.2, for all the world's data. The upper graph is for the Cherenkov results and the lowest for the electron size spectrum. The dashed curves for the Cherenkov and electron spectrum graph are the SSM predictions; that for Electron Size Spectrum includes an 'experimental error' with $\sigma_{exp} = 0.16$.

the problem of the origin of the knee, because they leave *no room for the Galactic Modulation model* with its smooth and regular steepening of all the constituent nuclei spectra.

3.2 Mass composition

The primary mass composition in the knee region is still a matter of hot debate. The problem is that direct measurements in space do not yet reach the important PeV region. All the studies of the mass composition there are indirect and based on the ratios between different shower components. The range of conclusions is highly disparate; however there has been progress here in the last few years. Most of the experiments now give convergent results and conclude that the mass composition becomes heavier beyond the knee.

3.3 Anisotropy

The anisotropy of arrival directions can provide information about the origin of the knee. The overall situation has been discussed by us in². We only underline that both the amplitude and the phase of the first harmonic show sharp changes in the PeV-region. It is another argument in favour of an astrophysical origin and against the interaction model of the knee.

4 Single Source Model of the Knee (SSM)

There is a general conjecture, based on energy and theoretical arguments, that supernova explosions are responsible for the formation of the cosmic ray energy spectrum below, and possibly even beyond, the knee. The intensity of their explosions is correlated with the star forming regions, whose properties: density and temperature of the interstellar gas, strength and irregularity of magnetic fields *etc* vary over a wide range. Thus, any kind of averaging over the range

of supernovae would eventually result in a smoothly varying cosmic-ray spectrum. In 1997 we put forward a model in which the knee is formed by the explosion of just *a single, nearby and recent supernova*³.

4.1 Shape of the primary energy spectrum

The shape of the primary energy spectrum in SSM is shown in Figure 2. The spectrum of cosmic rays caused by the explosion of single SN protrudes through the smooth background formed by many other sources. We attribute the knee to the contribution of oxygen nuclei, because:

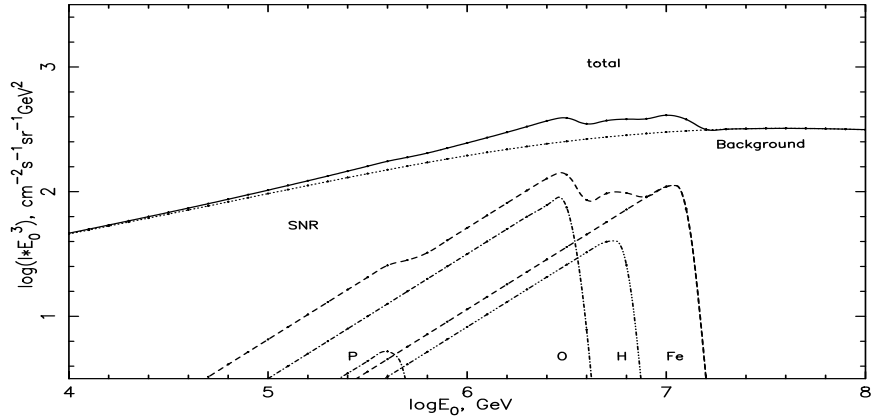


Figure 2: The Single Source Model of the primary energy spectrum. Structure of the spectrum: SNR denotes the contribution from the single supernova and lines denoted as P, O, H, Fe - the contribution of the constituent spectra from protons, oxygen, heavy (Ne-S) and iron nuclei correspondingly. The background spectrum is assumed to be due to many (unspecified) sources.

- (i) its position at 3 PeV corresponds to the theoretical prediction for oxygen;
- (ii) its position and intensity stand well at the extrapolation from the results of direct measurements at lower energies;
- (iii) it helps to understand the sharpness of the EAS size spectra, because the nuclei-initiated showers have smaller fluctuations in their development and the sharp cutoff in the primary energy spectrum should not be diluted when transferred to the EAS size spectrum.

4.2 Mass composition

- (i) If the knee is attributed to oxygen then the second peak is probably associated with iron. This assumption explains well the existence of the second peak and its separation from the knee by a factor proportional to the charge (see SSM based curves in Figure 1);
- (ii) in the SSM the primary mass should rise with energy beyond the knee, which agrees with the results of the experiments mentioned in subsection 3.2.

4.3 Anisotropy

Despite the fact that the source in the SSM is recent and nearby it is certain that it should not create a very strong anisotropy. If our interpretation of the mass composition, i.e. the dominance of oxygen and iron in the peaks is correct, then the peak energies correspond to a rigidity of 0.4 PV. The maximum Larmor radius of all the nuclei at a rigidity of 0.4 PV in the surroundings of the solar system is about 0.1 pc. The propagation of the cosmic rays from the source is definitely by diffusion and the anisotropy is therefore determined just by the gradient of the very local cosmic-ray density. The second factor which might be important is the location of the solar system with respect to the shock front. If we are inside it, the cosmic rays are highly isotropized and even their gradient is not easy to detect. Perhaps the changes of amplitude and phase of the first harmonic are the only imprints of the nearby source on the generally isotropic flux of the cosmic rays at PeV energies.

5 On the way to the identification of the single source

There are not many known single sources which could be classified as ‘nearby and recent’ *ie* within the range of a few hundred parsecs and a few hundred thousand years (Figure 3).

The first step in the identification of the source responsible for the knee is to determine whether we are inside or outside the shock front. We argue that the case when we are *inside the shock* (or only just outside) is preferable, compared with the opposite case when we are far outside it⁴. We remark that this conclusion helps us to understand also the relatively small amplitude of the anisotropy in the knee region. The typical propagation of the shock wave from the supernova explosion, taken from the Berezhko *et al.* calculations⁵, is shown in Figure 3 by the dotted line. The sources inside the shock should lie below this line.

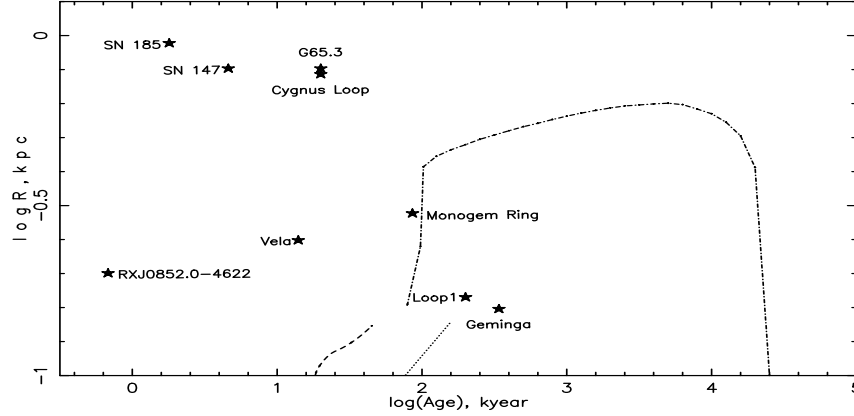


Figure 3: Plot of recent and nearby sources, which might be responsible for the formation of the knee. The dotted line shows the typical propagation of the shock front. The dashed and dash-dotted lines are derived from the comparison of the energy contained in cosmic rays for our Single Source and the energy content of the cosmic rays accelerated by the supernova remnant in the calculations of Berezhko *et al.*⁵ and in our model⁶. The possible source candidates should lie inside the area delimited by these lines.

Another step in the identification of the source might be based on the analysis of the energy content of the source. The candidate for the source could not be too far from the solar system or too close to the moment of the explosion in order to have enough energy in cosmic rays and give the required contribution to the cosmic-ray flux at the knee. Comparison of the energy density in our single source (Figure 2) with the relevant calculations⁵ and also using our model of the SN explosion⁶ indicates that our single source should lie to the right of the dashed line and inside the area limited by the dash-dotted line in Figure 3, closer to its left and lower corner. At the moment, the sources which gave birth to Loop I, Monogem Ring and the Geminga pulsar are the most favorable contenders. However, the problem of the identification is still with us.

6 Conclusion

The recent results on EAS allow us to conclude that: a) the knee observed in the cosmic-ray spectrum at about 3 PeV has an astrophysical origin; b) the sharpness and the fine structure of the knee rule out the Galactic Modulation Model as the origin of the knee; c) the most likely model of the knee is the *source* model in which the knee appears as the result of the explosion of a single, recent, nearby supernova.

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